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Improved Meteorological Measurements from Buoys and Ships (IMET): Preliminary Comparison of Pyranometers

by

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Technical Report

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Abstract

Three different types of pyranometers (two of each) are tested and evaluated. The sensors include the Eppley Precision Spectral Pyranometer (PSP) which meets the World Meteorological Organization (1965) criteria for a first class pyranometer, the Eppley 8-48 Black and White Pyranometer (second class) and the Hollis MR-5 Silicon Photovoltaic Pyranometer (third class).

Table of Contents

1 Introduction

Several components of the U.S. effort in the World Ocean Circulation Experiment (WOCE) will require observations of air-sea radiation fluxes from both ships and buoys. A group at Woods Hole Oceanographic Institution (WHOI) is developing and testing instrumentation to provide Improved Meteorological measurements (IMET) to meet the requirements of these WOCE components. Here we report on the performance of pyranometers.

Pyranometers are sensors that measure total (global) sun and sky radiation when installed facing up in a horizontal plane tangent to the earth's surface. The World Meteorological Organization (WMO, 1965) defines three classes of pyranometers on the basis of their accuracy and overall system performance. The bases for the classification are given in Table 1. First class pyranometers display the greatest accuracy while third class pyranometers display the least.

A maximum error of 10 Wm^{-2} is sought for daily averaged incident solar irradiance. This includes measurement errors due to the sensor, contamination by sea salt and/or sea spray, and platform motions (Katsaros and DeVault, 1986).

2 Description of Sensors

Three different types of pyranometers (two of each) are examined. The Eppley Precision Spectral Pyranometer (PSP) meets the criteria for a first class pyranometer and is the operational standard for solar radiation measurements in the United States (Houghton, 1985). The PSP is commonly used as a secondary standard to calibrate second and third class pyranometers (e.g., Aceves-Navarro *et al.*, 1988). The sensor is a circular, plated (copper-constantan) wire-wound multi-junction thermopile which is temperature compensated to render the response independent of ambient temperature. The receiver is coated with Parson's black lacquer and covered with two concentric clear Schott WG 7 optical glass domes which are transparent for wavelengths between 0.285 to 2.8 microns.

The Eppley Black and White Pyranometer (8-48) meets the WMO (1965) criteria for a second class pyranometer. The insolation detector is a differential wire-wound thermopile made by electroplating copper on to constantan. The hot-junction receivers are coated with 3M Black Velvet and the cold-junction receivers are whitened with barium sulfate. A single Schott WG 7 optical glass dome is used to protect the sensor.

The Hollis MR-5 is a silicon photovoltaic solar cell that meets the criteria for a third class pyranometer. This type of pyranometer was first developed at Bell Laboratories in 1954 (Coulson, 1975) as a simple and inexpensive alternative for measuring solar radiation. An advantage is the nearly instantaneous time response of approximately 10 microseconds. Although the absolute accuracy may not be very high, this type of pyranometer may be adequate for integrating over periods of a day or longer. Kerr *et al.* (1967) have obtained measurements with a photovoltaic solar cell over a period of several months (one day integration periods) that yielded standard errors of up to $\pm 3.8\%$ when compared to an Eppley pyranometer.

The inaccuracies of photovoltaic solar cells are due to the characteristics of the sensor itself. The relative spectral response of the sensor does not extend uniformly over the full incoming solar radiation spectrum. The response is negligibly small at wavelengths shorter than 0.4 microns and longer than 1.1 microns with a relatively sharp maximum at 0.85 microns (Coulson, 1975). Also the response deviates from the ideal cosine law with the angle of incident radiation.

The MR-5 is calibrated at the factory against a thermal response pyranometer. This sensor does not have an optical glass dome.

Table 2 contains a summary of the manufacturer specifications for these pyranometers.

3 Data

The pyranometers are located on roof top on the Smith Building in Woods Hole and have an unobstructed view of the sky. These pyranometers are leveled to the same height on a platform (Figure 1). The signal outputs are amplified and then digitized by a Metrabyte 12 bit analog-to-digital board internal to a NEC APC-IV computer. Data are sampled once per second and are recorded as 7.5 minute block averages. The pyranometer calibration coefficients and gain amplifications are listed in Table 3.

4 Analysis

Approximately three months of data are grouped into weekly data sets and all evening insolation values (less than 5 Wm^{-2}) are removed. One of two Eppley PSPs (27412F3) is arbitrarily chosen to compare against the other pyranometers.

Weekly mean differences (absolute and percentage) between the pyranometer in question and PSP 27412F3 are calculated for each data set (Tables 4A–8A).

Linear regression curves are computed to examine the relationship between two variables. The predicted value of the pyranometer in question as a function of PSP 27412F3 is given by

$$y' = A + Bx \tag{1}$$

where A and B are the intercept and slope, respectively, of a straight line. The measure of the scatter about the regression line is given by

$$SE = \sqrt{\frac{1}{N}\sum(y - y')^2} \tag{2}$$

where SE is the standard error, y is the dependent variable and N is the number of records. The correlation coefficient is computed for each linear regression. These values are shown in Tables 4B–8B.

The Eppley PSPs show excellent agreement with each other (Table 4). Absolute weekly mean differences never exceed 5 Wm^{-2} with percentage differences typically less than 1%. The standard errors range from 4 to 6 Wm^{-2} with the exception of weeks 5 through 7 when PSP 27413F3 displayed slightly erratic behavior in several data points causing larger standard errors of 12 to 16 Wm^{-2}. Scatter plots are shown in Figures 2 and 3. Individual differences are typically less than 10 Wm^{-2}.

Both Eppley 8-48 pyranometers also show excellent agreement with the Eppley PSP (Tables 5 and 6). Absolute mean differences generally do not exceed 5 Wm^{-2} or 1%. Linear regressions show standard errors generally ranging from 6 to 10 Wm^{-2}, indicating slightly more scatter in the 8-48 values than that seen with the PSP. Scatter plots for sensors 9698 and 9891 are shown in Figures 4–7. A positive difference bias exists for insolation values under 800 Wm^{-2} while a negative bias exists for insolation values greater than 800 Wm^{-2}.

After FASINEX (Stage and Weller, 1985; 1986), five buoys, each with an Eppley 8-48 pyranometer measured daily total insolation to within 3 percent of each other when deployed in a post-experiment intercalibration (Weller *et al.*, 1990). Pre- and post-deployment (over a ten month period) factory calibrations also agree to within 3 percent.

The Hollis MR-5 sensors give insolation values showing significant drift over the relatively short period of time that data was acquired. Sensor 5-180 displays a positive weekly mean difference of approximately 30 Wm^{-2} for the first four weeks then abruptly changes over the next several weeks to a negative bias of approximately -25 Wm^{-2} (Table 7). Sensor 5-205 also drifts towards more negative biases from approximately -15 to -70 Wm^{-2} in a twelve week period. Linear regressions showed standard errors typically less than 15 Wm^{-2}. This is significantly more scatter than seen with the PSP or 8-48 but is fairly typical of photovoltaic solar cells (Aceves-Navarro *et al.*, 1988). Scatter plots are shown for these two sensors in Figures 8–11. Large individual differences of up to 100 Wm^{-2} exist at high insolation values.

5 Summary and Conclusions

Solar irradiance data from three different pyranometers (two of each) are analyzed and discussed. One of two Eppley Precision Spectral Pyranometers is arbitrarily chosen to compare with the remaining five sensors.

The Eppley PSPs show excellent agreement with each other. Weekly mean differences are 1% or less than 4 Wm^{-2}. Linear regression analysis shows minimal scatter with standard errors of 4 to 6 Wm^{-2}.

The Eppley 8-48 also shows excellent agreement with the PSP. Absolute weekly mean differences never exceed 5 Wm^{-2} or about 1%. Linear regression also shows excellent agreement but the standard errors are slightly larger from 6 to 10 Wm^{-2} indicating slightly more scatter than observed with the PSP.

The Hollis MR-5 silicon photovoltaic sensors show very good correlations with weekly standard errors of 10 to 15 Wm^{-2}. However, the sensors display significant drifts in insolation values. Both sensors drifted approximately 55 to 60 Wm^{-2} over a 3 month period towards a more negative bias. It is not known what is causing these drifts.

Acknowledgements

The authors wish to thank Ovid Forier for his help in designing and constructing much of the circuitry in the data acquisition system. The authors also wish to thank Barbara Gaffron for her helpful suggestions and comments.

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World Meteorological Organization, 1965. Measurement of radiation and sunshine. Guide to Meteorological Instruments and Observing Practices. WMO No. 8, Geneva, Switzerland.

Appendix A

Manufacturers Addresses

Eppley Laboratory Inc.
12 Sheffield Avenue
Newport, Rhode Island 02840
(401) 847-1020

Hollis International Limited
17 Clinton Drive
Hollis, New Hampshire 03049
(603) 882-5017

Table 1: WMO (1965) Classification of Pyranometers

	1st class	2nd class	3rd class
Resolution (Wm^{-2})	1	5	10
Stability (change per year - %)	1	2	5
Temperature (maximum error due to changes of ambient temperature - %)	1	2	5
Selectivity (maximum error due to departure from assumed spectral response - %)	1	2	5
Linearity (maximum error due to nonlinearity not accounted for - %)	1	2	3
Time constant (maximum)	25 sec	1 min	4 min
Cosine response (deviation from that assumed, taken at Sun elevation 10 deg on clear day - %)	3	5–7	10
Azimuth response (deviation from that assumed, taken on clear day - %)	3	5–7	10

Table 2: Pyranometer Specifications

	Eppley PSP	Eppley 8-48	Hollis MR-5
Sensitivity (microvolts / Wm^{-2})	9	11	72
Maximum Error Due to Temperature (-20 to $+40°C$)	1%	1.5%	1.5%
Linearity with Intensity	0.5%	1%	1%
Energy Flux Range (Wm^{-2})	0–2800	0–1400	0–1400
Cosine Response (0–70 deg)	1%	2%	*1.5%
(70–80 deg)	3%	5%	–
Time Response (sec)	1	3–4	< 1
Cost	$1790	$1150	$250

* Cosine response from 0–80 degrees zenith.

Table 3: Pyranometer Calibration Information

Pyranometer	Serial Number	Calibration Coefficient (x 1E-6)	Gain
		$\mu V/W\ m^{-2}$	
Eppley PSP	27412F3	7.74	370
Eppley PSP	27413F3	7.85	370
Eppley 8-48	9698	11.11	267
Eppley 8-48	9891	10.77	267
Hollis MR-5	5-180	71.71	37
Hollis MR-5	5-205	71.71	37

Table 4: Comparison of an Eppley Precision Spectral Pyranometer (27413F3) against an Eppley Precision Spectral Pyranometer (27412F3).

A — Weekly mean values and differences.

Julian Days (1989)	Number of Records	27413F3 (Wm^{-2})	27412F3 (Wm^{-2})	Difference (Wm^{-2})	(%)
101–107	647	334.1	334.4	-0.4	-0.1
107–114	705	443.5	443.6	-0.1	-0.0
114–121	713	419.9	421.2	-1.2	-0.3
121–128	802	412.8	415.1	-2.4	-0.6
129–135	587	300.1	303.9	-3.8	-1.2
135–142	793	423.4	428.3	-4.8	-1.1
143–150	732	364.3	368.8	-4.5	-1.2
150–156	701	397.7	402.0	-4.2	-1.1
157–163	619	283.6	286.4	-2.8	-1.0
163–170	792	335.7	338.5	-2.8	-0.8
170–176	719	473.1	477.6	-4.5	-0.9
178–184	686	455.8	459.5	-3.7	-0.8

B — Linear regression coefficients where A is the Y-intercept, B is the slope, and R is the correlation coefficient.

Julian Days (1989)	Number of Records	A	B	R	Standard Error (Wm^{-2})
101–107	647	-0.7	1.001	0.9998	5.2
107–114	705	-2.4	1.005	0.9999	4.8
114–121	713	-0.7	0.999	0.9999	5.3
121–128	802	-0.7	0.996	0.9999	3.9
129–135	587	-0.2	0.988	0.9986	16.0
135–142	793	-4.7	1.000	0.9984	16.9
143–150	732	-1.1	0.991	0.9992	12.4
150–156	701	-1.6	0.993	0.9998	5.6
157–163	619	-1.7	0.996	0.9998	5.4
163–170	792	-1.6	0.997	0.9999	4.7
170–176	719	-1.9	0.995	0.9998	6.4
178–184	686	-0.6	0.993	0.9999	5.8

Table 5: Comparison of an Eppley Black and White Pyranometer (9698) against an Eppley Precision Spectral Pyranometer (27412F3).

A — Weekly mean values and differences.

Julian Days (1989)	Number of Records	9698 (Wm^{-2})	27412F3 (Wm^{-2})	Difference (Wm^{-2})	(%)
101–107	647	337.1	334.4	2.6	0.8
107–114	705	448.1	443.6	4.6	1.0
114–121	713	424.2	421.2	3.1	0.7
121–128	802	417.9	415.1	2.8	0.7
129–135	587	302.8	303.9	-1.0	-0.3
135–142	793	430.0	428.3	1.7	0.4
143–150	732	371.3	368.8	2.5	0.7
150–156	701	403.6	402.0	1.7	0.4
157–163	619	284.8	286.4	-1.6	-0.5
163–170	792	337.8	338.5	-0.7	-0.2
170–176	719	480.2	477.6	2.6	0.5
178–184	686	461.8	459.5	2.2	0.5

B — Linear regression coefficients where A is the Y-intercept, B is the slope, and R is the correlation coefficient.

Julian Days (1989)	Number of Records	A	B	R	Standard Error (Wm^{-2})
101–107	647	3.3	0.998	0.9996	7.5
107–114	705	8.3	0.992	0.9997	8.0
114–121	713	4.1	0.998	0.9996	8.5
121–128	802	4.5	0.996	0.9998	6.6
129–135	587	0.7	0.994	0.9995	9.8
135–142	793	2.7	0.998	0.9994	10.3
143–150	732	3.2	0.998	0.9995	9.7
150–156	701	2.7	0.997	0.9998	5.6
157–163	619	-0.2	0.995	0.9996	7.5
163–170	792	-0.1	0.998	0.9998	5.7
170–176	719	5.3	0.994	0.9998	6.3
178–184	686	5.5	0.993	0.9999	5.7

Table 6: **Comparison of an Eppley Black and White Pyranometer (9891) against an Eppley Precision Spectral Pyranometer (27412F3).**

A — Weekly mean values and differences.

Julian Days (1989)	Number of Records	9891 (Wm^{-2})	27412F3 (Wm^{-2})	Difference (Wm^{-2})	(%)
101–107	647	338.2	334.4	3.8	1.1
107–114	705	449.4	443.6	5.8	1.3
114–121	713	423.5	421.2	2.3	0.6
121–128	802	416.6	415.1	1.4	0.3
129–135	587	303.3	303.9	-0.6	-0.2
135–142	793	428.7	428.3	0.4	0.1
143–150	732	371.1	368.8	2.3	0.6
150–156	701	403.1	402.0	1.1	0.3
157–163	619	287.1	286.4	0.7	0.3
163–170	792	337.6	338.5	-0.9	-0.3
170–176	719	478.4	477.6	0.8	0.2
178–184	686	461.6	459.5	2.1	0.5

B — Linear regression coefficients where *A* is the Y-intercept, *B* is the slope, and *R* is the correlation coefficient.

Julian Days (1989)	Number of Records	A	B	R	Standard Error (Wm^{-2})
101–107	647	4.9	0.997	0.9997	7.2
107–114	705	9.9	0.991	0.9996	8.3
114–121	713	6.6	0.990	0.9996	9.0
121–128	802	6.2	0.989	0.9997	7.9
129–135	587	0.7	0.996	0.9996	8.3
135–142	793	4.1	0.991	0.9994	10.3
143–150	732	4.2	0.995	0.9995	9.2
150–156	701	5.0	0.990	0.9997	7.2
157–163	619	-0.6	1.005	0.9997	6.7
163–170	792	1.1	0.994	0.9998	5.6
170–176	719	6.9	0.987	0.9997	7.8
178–184	686	7.6	0.988	0.9998	7.0

Table 7: Comparison of a Hollis Silicon Cell Pyranometer (5-180) against an Eppley Precision Spectral Pyranometer (27412F3).

A — Weekly mean values and differences.

Julian Days (1989)	Number of Records	5-180 (Wm^{-2})	27412F3 (Wm^{-2})	Difference (Wm^{-2})	Difference (%)
101–107	647	369.0	334.4	34.6	10.4
107–114	705	476.7	443.6	33.1	7.5
114–121	713	452.2	421.2	31.0	7.4
121–128	802	442.4	415.1	27.2	6.6
129–135	587	311.6	303.9	7.7	2.5
135–142	793	428.8	428.3	0.5	0.1
143–150	732	362.9	368.8	-5.9	-1.6
150–156	701	388.4	402.0	-13.6	-3.4
157–163	619	274.8	286.4	-11.6	-4.1
163–170	792	319.9	338.5	-18.6	-5.5
170–176	719	451.6	477.6	-26.1	-5.5
178–184	686	433.9	459.5	-25.6	-5.6

B — Linear regression coefficients where A is the Y-intercept, B is the slope, and R is the correlation coefficient.

Julian Days (1989)	Number of Records	A	B	R	Standard Error (Wm^{-2})
101–107	647	15.5	1.057	0.9990	12.9
107–114	705	19.0	1.032	0.9985	17.7
114–121	713	20.3	1.025	0.9990	14.8
121–128	802	11.7	1.037	0.9993	12.1
129–135	587	17.8	0.967	0.9979	19.0
135–142	793	19.2	0.956	0.9980	18.0
143–150	732	15.7	0.942	0.9986	15.0
150–156	701	13.3	0.933	0.9988	13.8
157–163	619	8.5	0.930	0.9987	13.0
163–170	792	3.4	0.935	0.9996	7.9
170–176	719	9.6	0.925	0.9996	7.9
178–184	686	8.1	0.926	0.9997	7.8

Table 8: **Comparison of a Hollis Silicon Cell Pyranometer (5-205) against an Eppley Precision Spectral Pyranometer (27412F3).**

A — Weekly mean values and differences.

Julian Days (1989)	Number of Records	5-205 (Wm^{-2})	27412F3 (Wm^{-2})	Difference (Wm^{-2})	Difference (%)
101–107	647	318.6	334.4	-15.8	-4.7
107–114	705	413.7	443.6	-29.9	-6.7
114–121	713	391.5	421.2	-29.7	-7.0
121–128	802	382.1	415.1	-33.0	-7.9
129–135	587	274.0	303.9	-29.9	-9.8
135–142	793	381.1	428.3	-47.2	-11.0
143–150	732	324.0	368.8	-44.8	-12.1
150–156	701	347.5	402.0	-54.5	-13.6
157–163	619	245.7	286.4	-40.7	-14.2
163–170	792	288.1	338.5	-50.4	-14.9
170–176	719	406.9	477.6	-70.7	-14.8
178–184	686	391.3	459.5	-68.3	-14.9

B — Linear regression coefficients where *A* is the Y-intercept, *B* is the slope, and *R* is the correlation coefficient.

Julian Days (1989)	Number of Records	*A*	*B*	*R*	Standard Error (Wm^{-2})
101–107	647	13.3	0.913	0.9989	12.0
107–114	705	18.2	0.892	0.9987	13.9
114–121	713	18.0	0.887	0.9989	13.4
121–128	802	11.3	0.893	0.9992	11.5
129–135	587	12.6	0.860	0.9985	14.5
135–142	793	14.1	0.857	0.9989	12.2
143–150	732	11.7	0.847	0.9988	12.4
150–156	701	11.5	0.836	0.9991	10.6
157–163	619	6.9	0.834	0.9976	15.9
163–170	792	2.3	0.844	0.9995	8.4
170–176	719	11.0	0.829	0.9996	7.4
178–184	686	10.8	0.828	0.9996	8.0

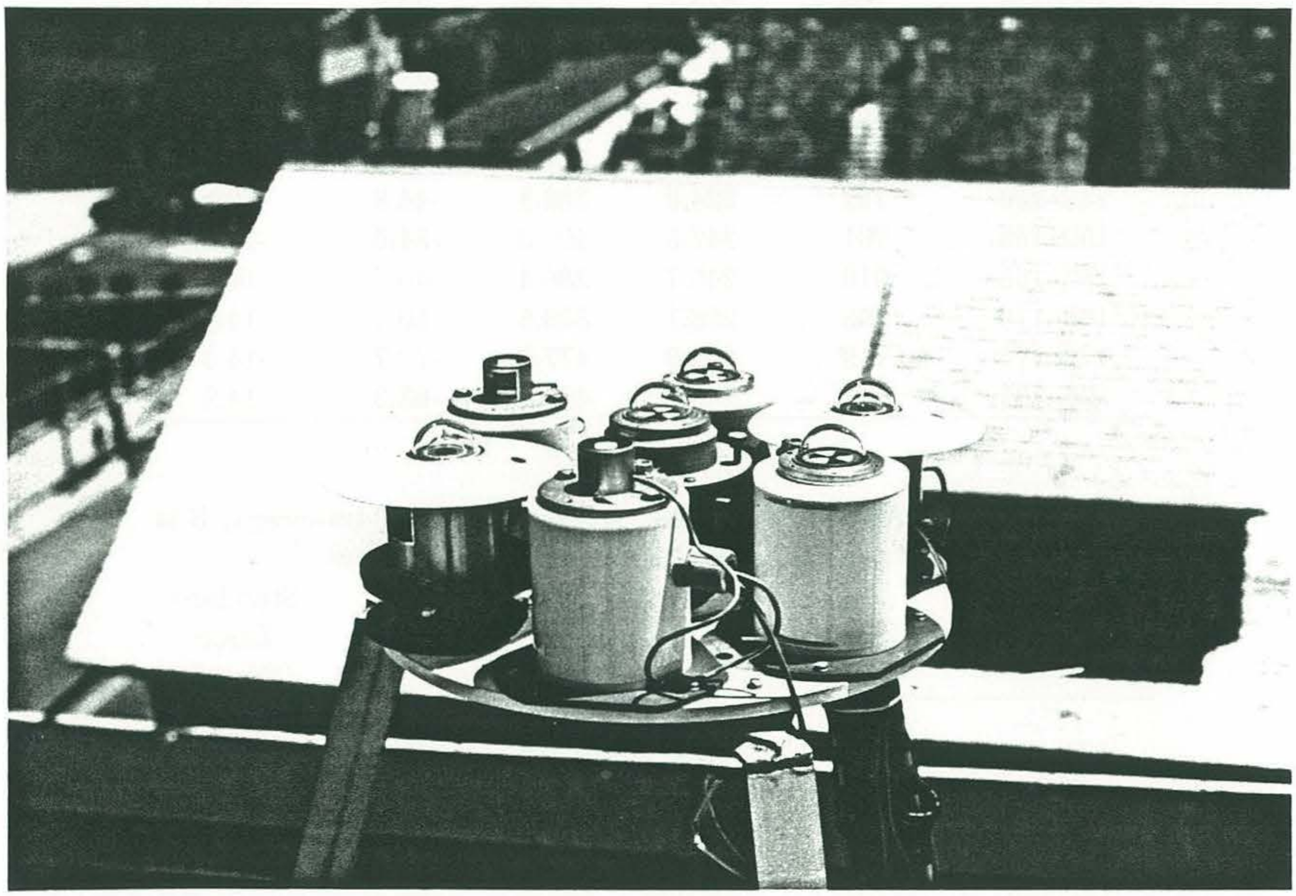

Figure 1: IMET pyranometers.

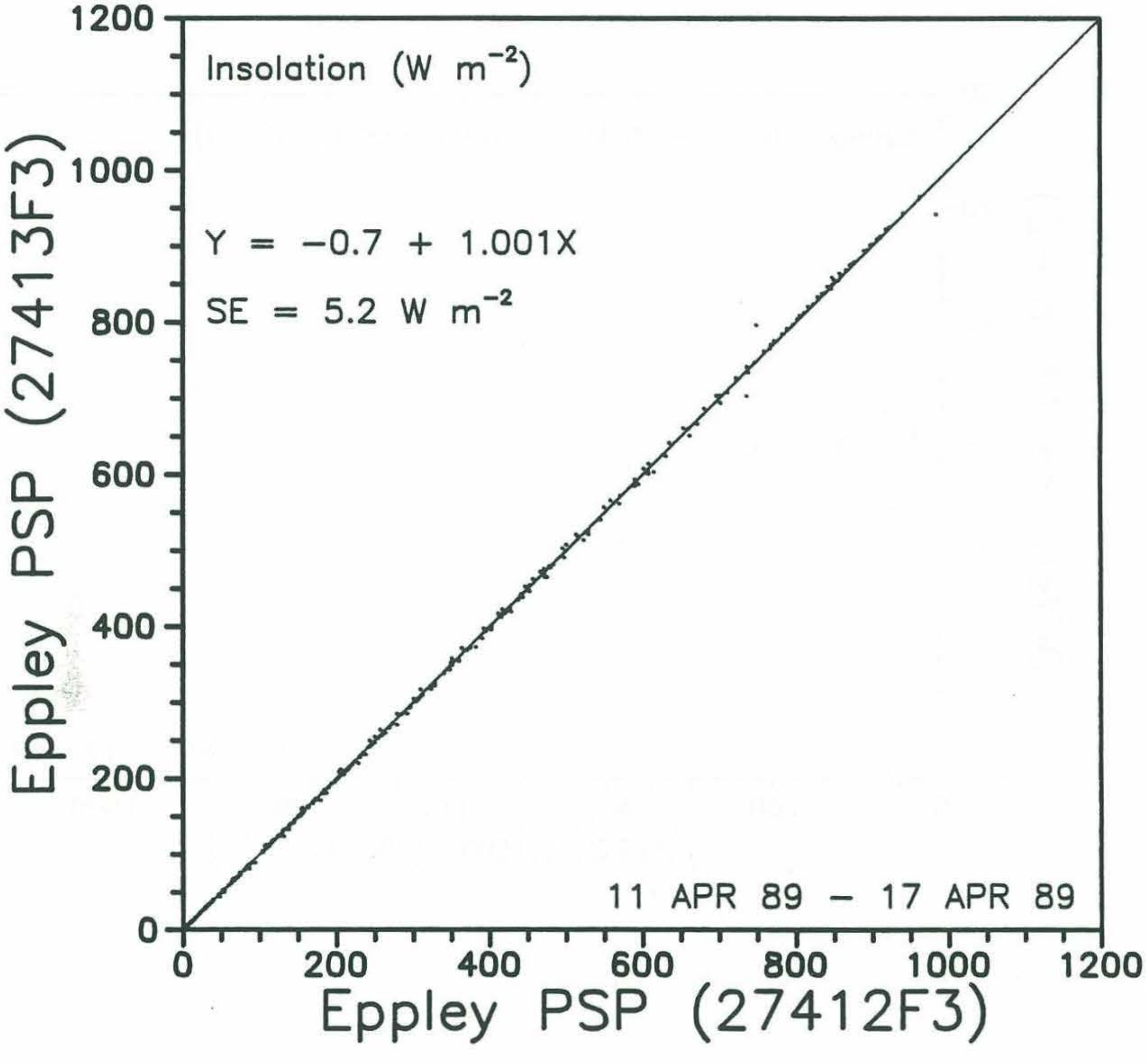

Figure 2: Scatter plot of Eppley PSP (27413F3) against Eppley PSP (27412F3).

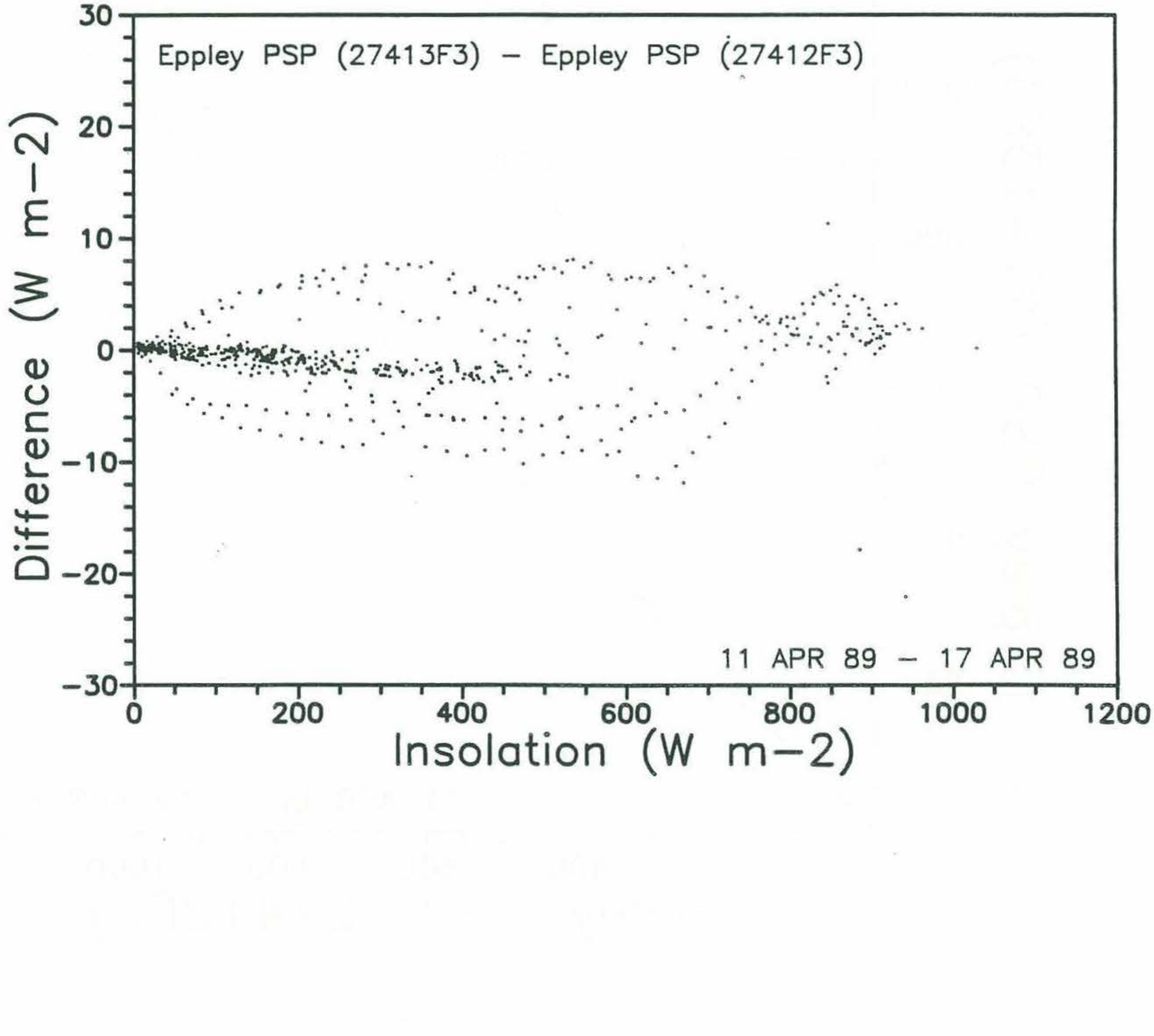

Figure 3: Scatter plot of insolation difference of Eppley PSP (27413F3) minus Eppley PSP (27412F3) as a function of insolation.

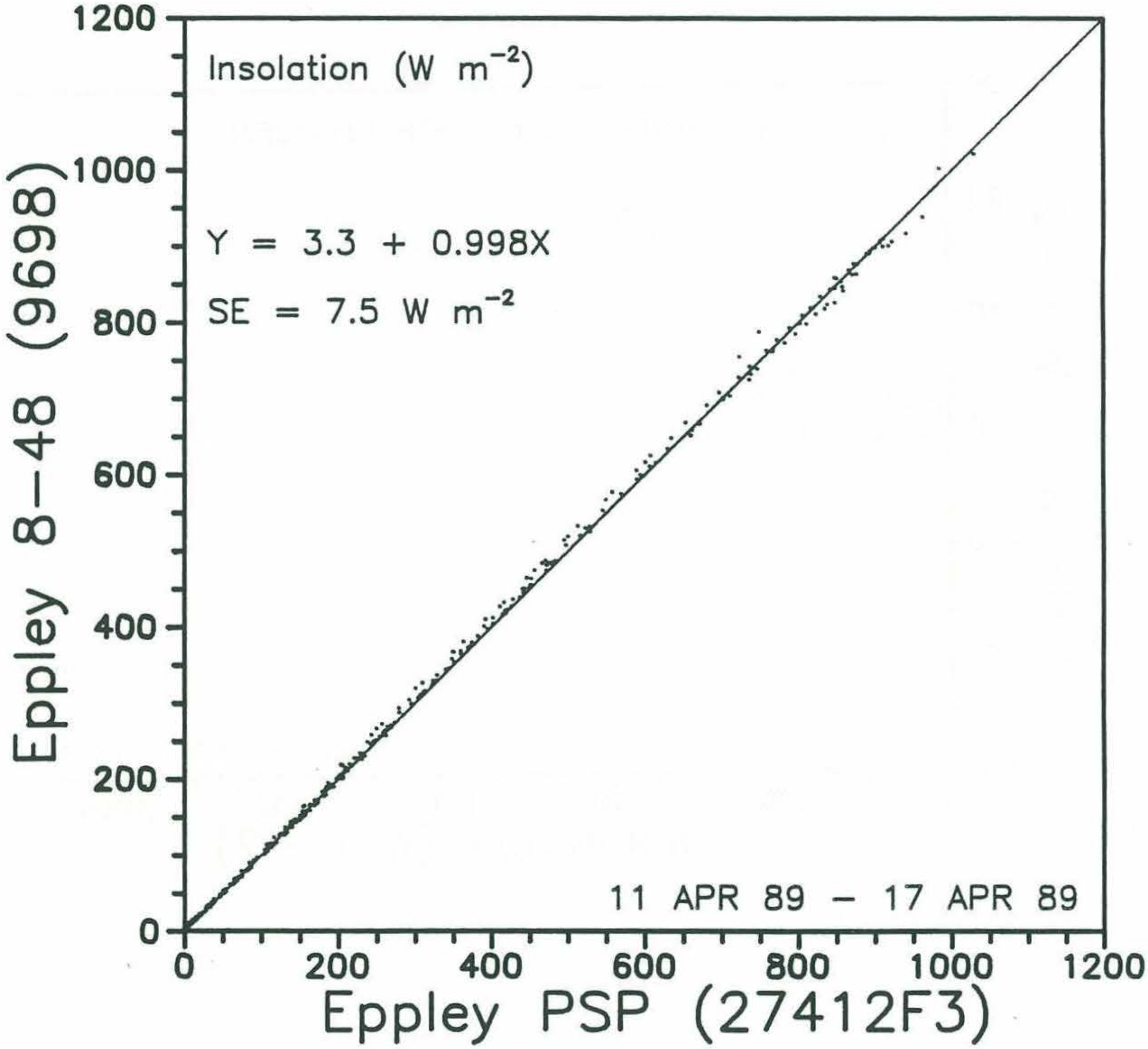

Figure 4: Scatter plot of Eppley 8-48 (9698) against Eppley PSP (27412F3).

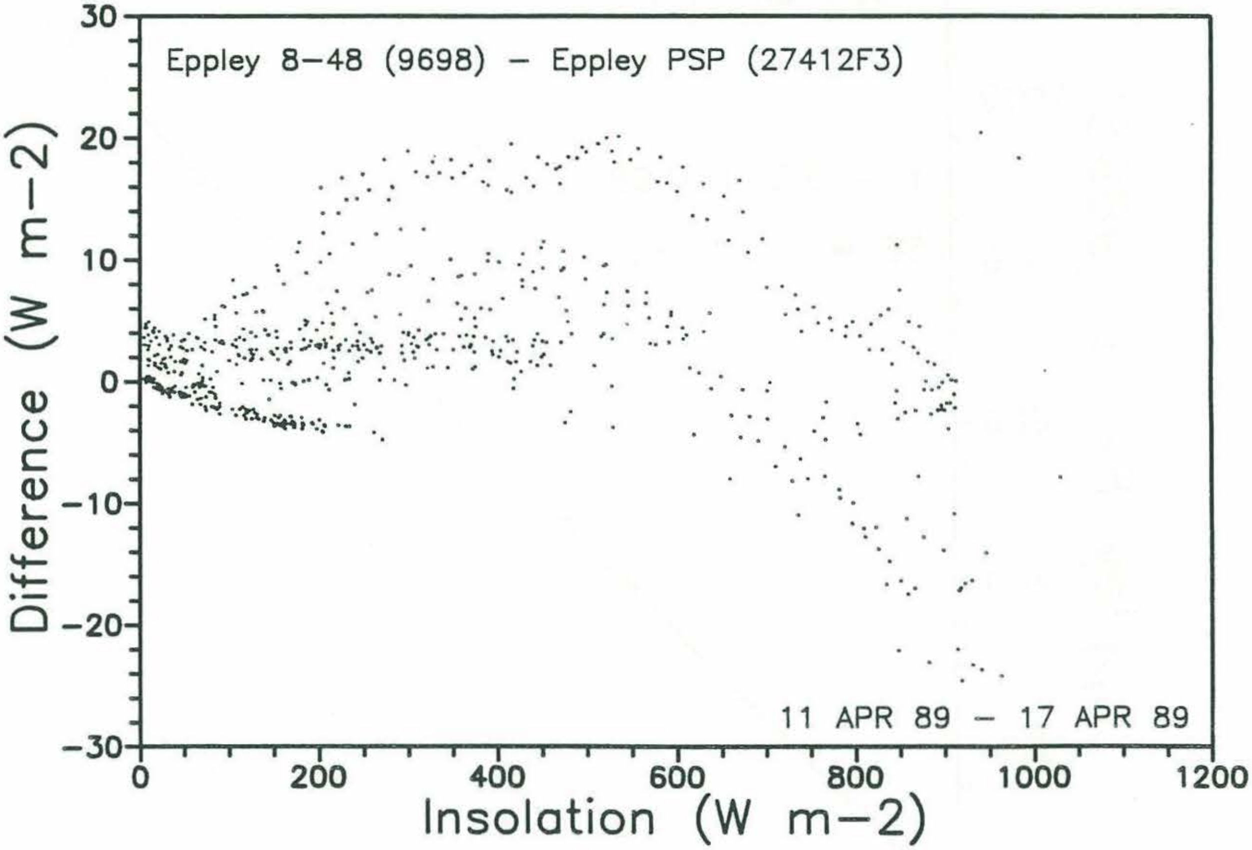

Figure 5: Scatter plot of insolation difference of Eppley 8-48 (9698) minus Eppley PSP (27412F3) as a function of insolation.

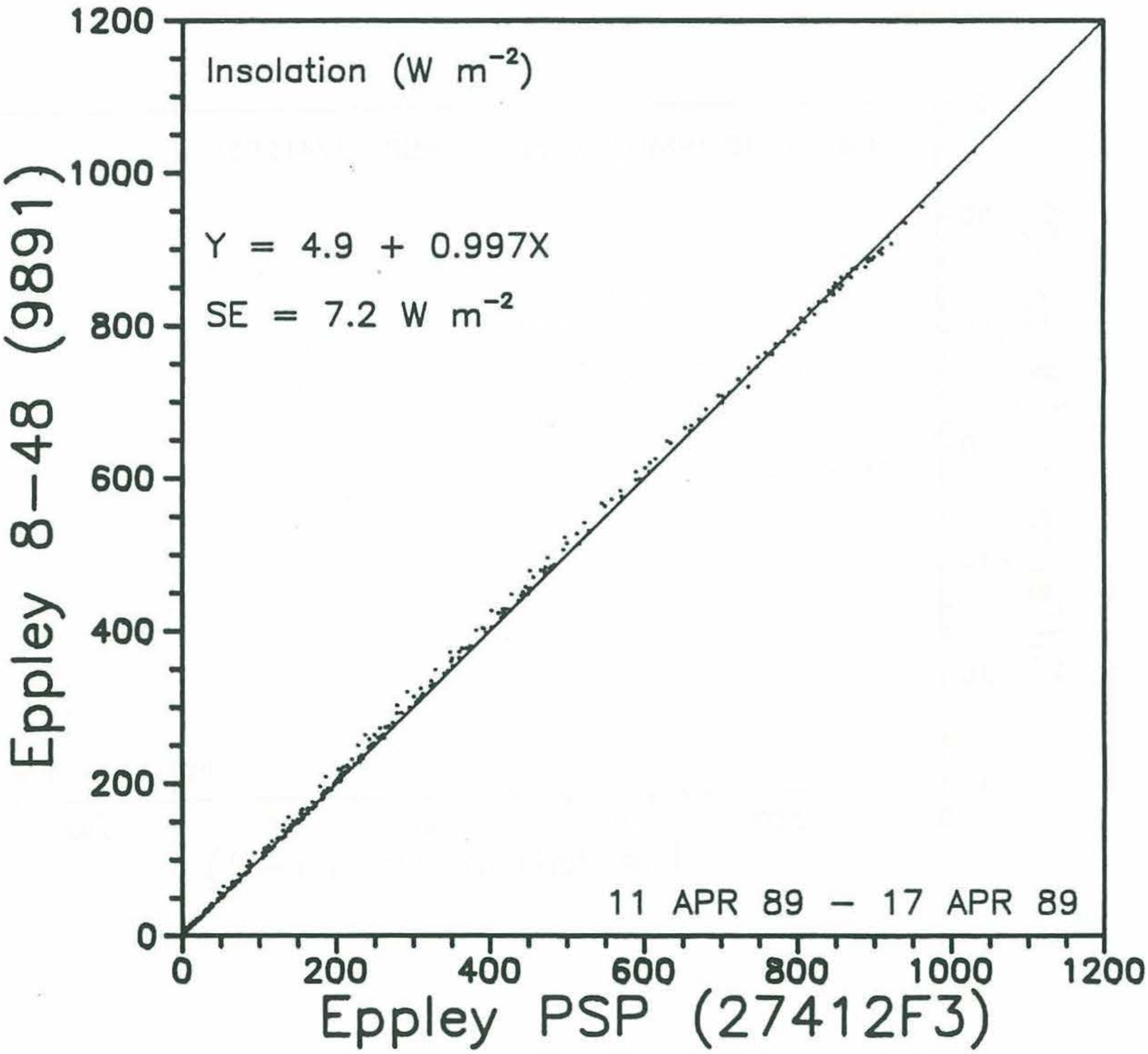

Figure 6: Scatter plot of Eppley 8-48 (9891) against Eppley PSP (27412F3).

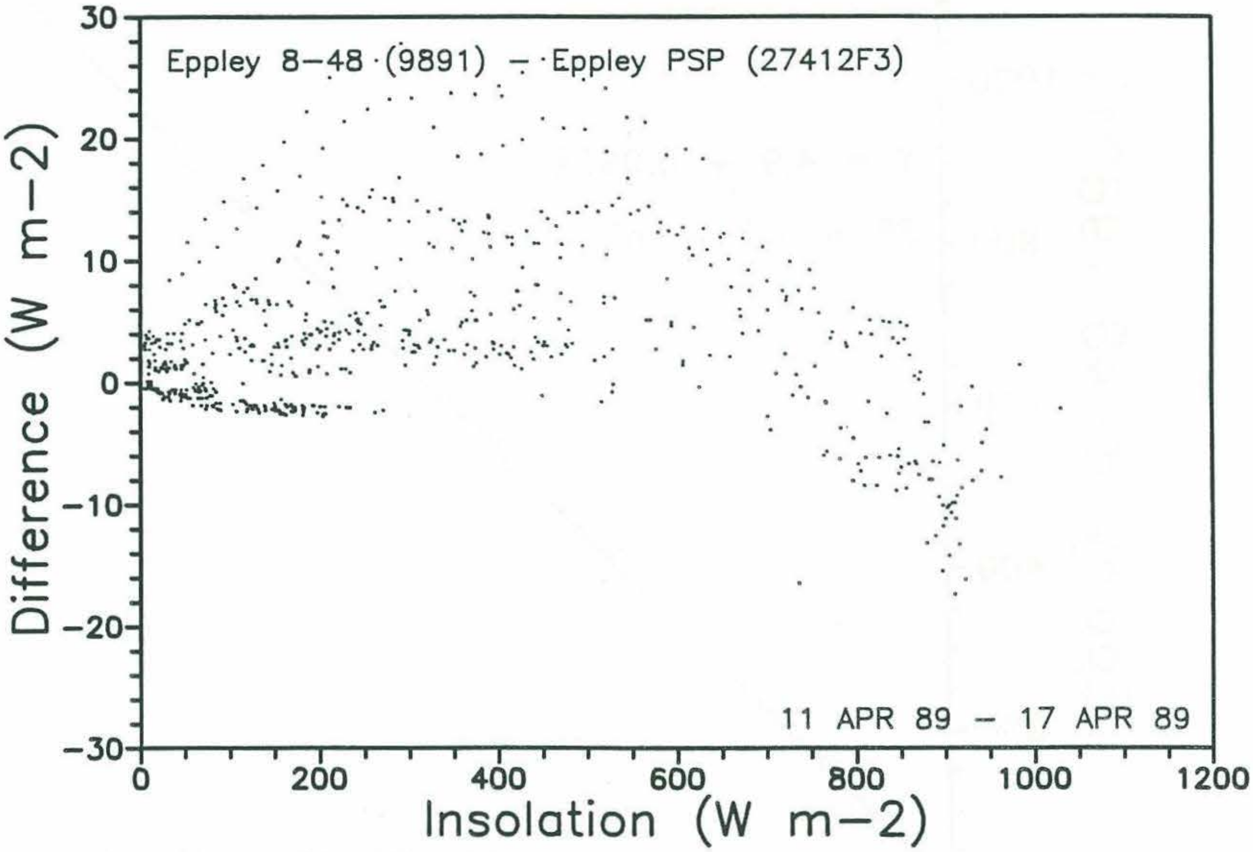

Figure 7: Scatter plot of insolation difference of Eppley 8-48 (9891) minus Eppley PSP (27412F3) as a function of insolation.

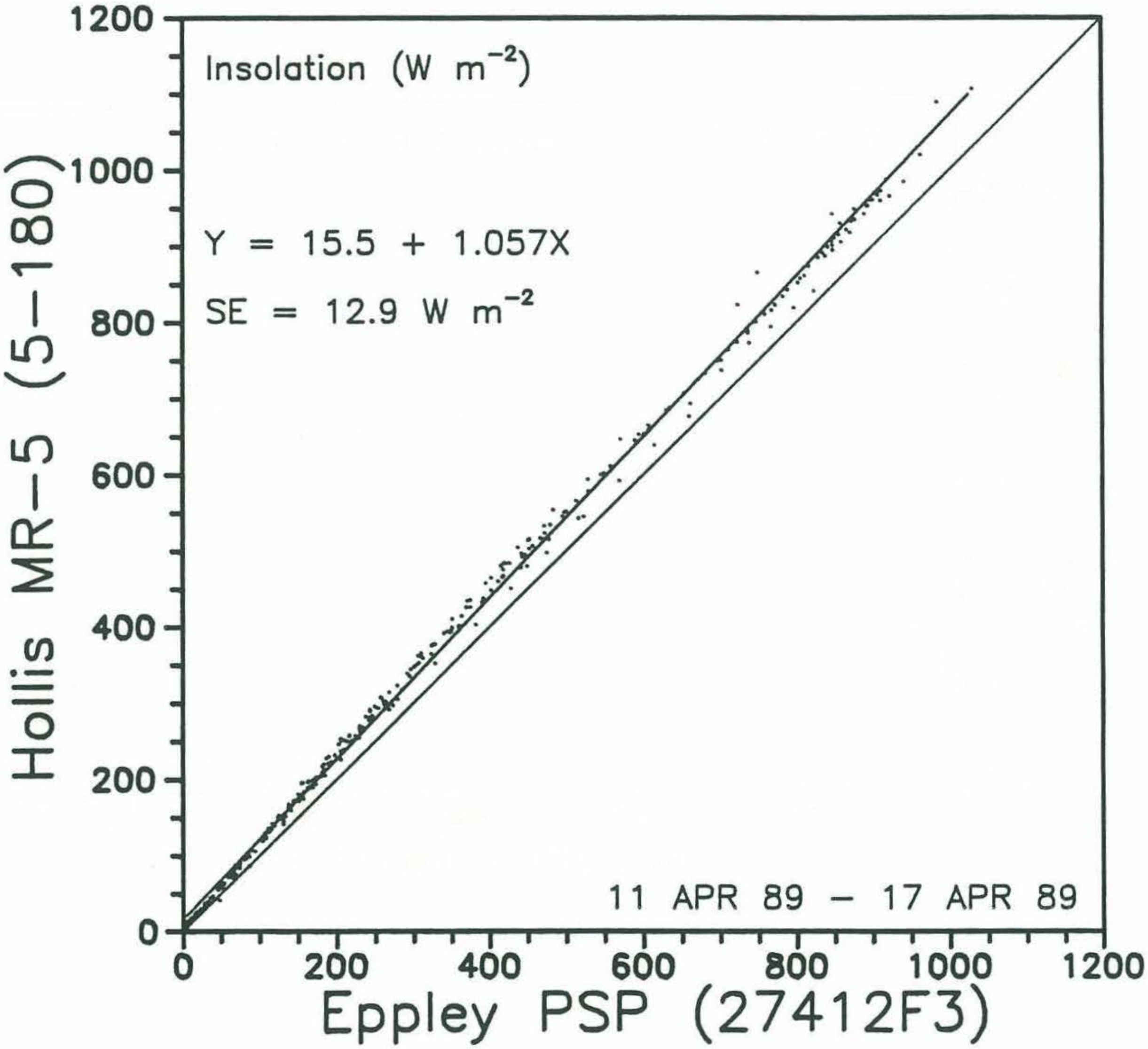

Figure 8: Scatter plot of Hollis MR-5 (5-180) against Eppley PSP (27412F3) with least squares fit.

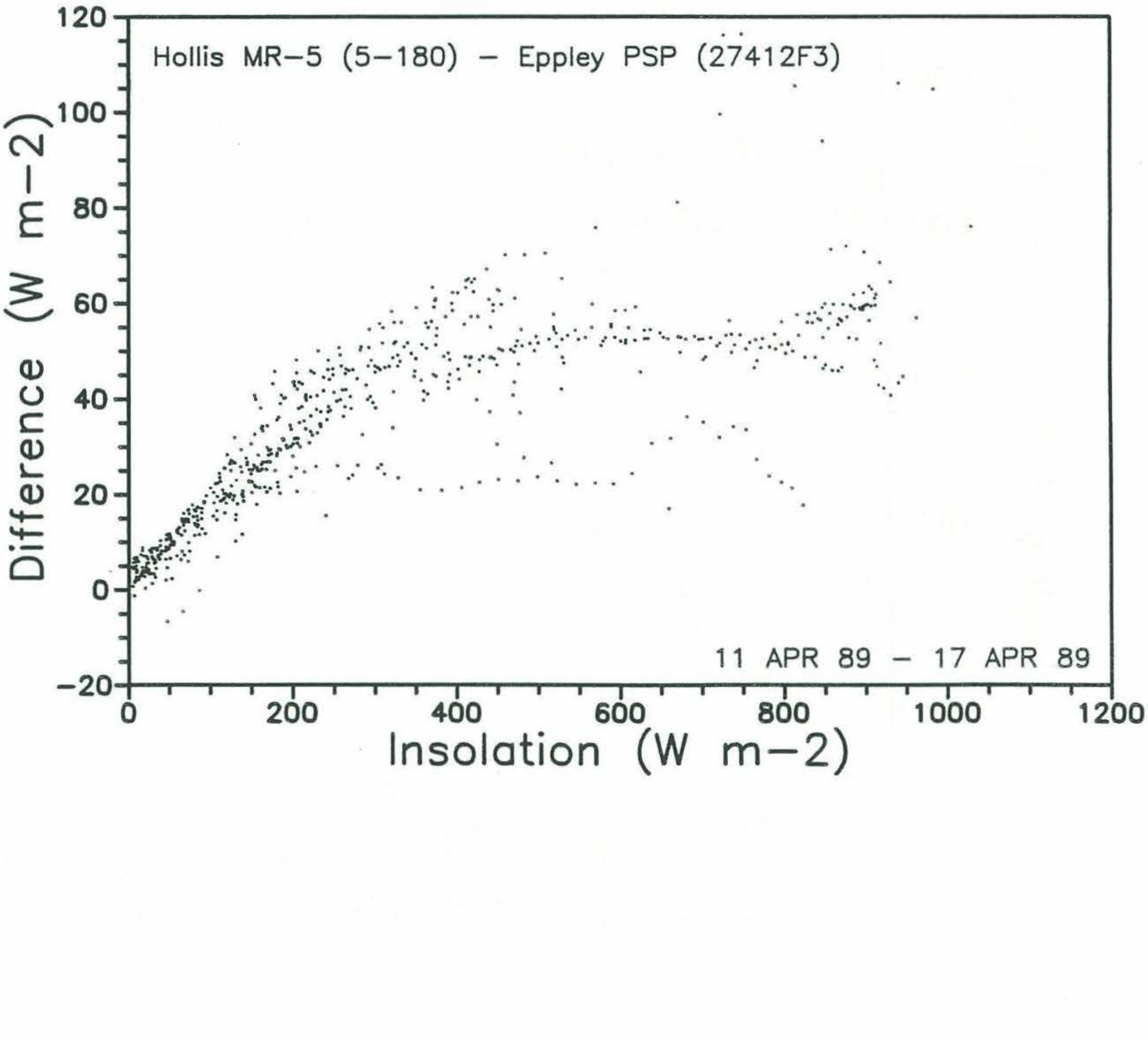

Figure 9: Scatter plot of insolation difference of Hollis MR-5 (5-180) minus Eppley PSP (27412F3) as a function of insolation.

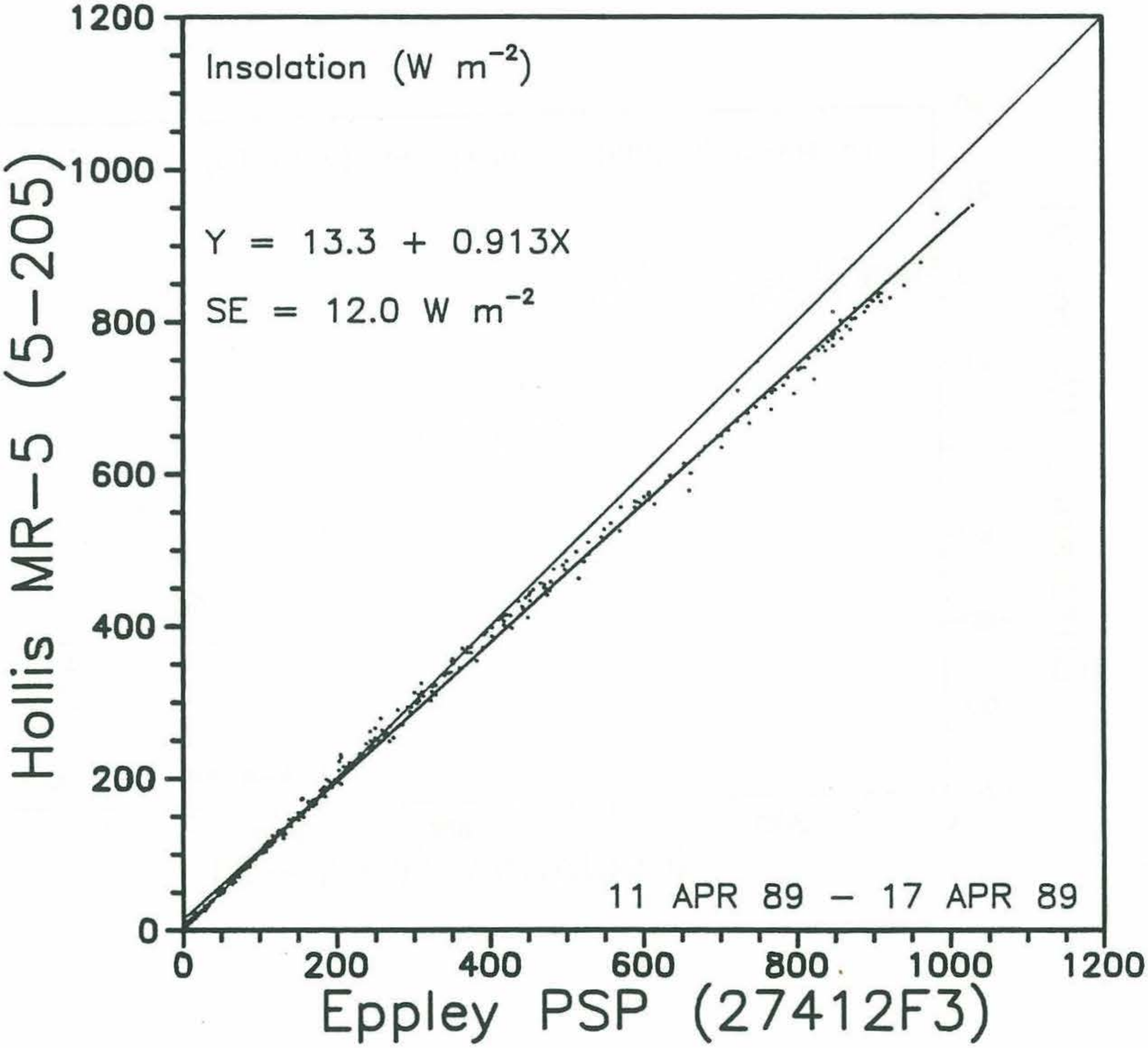

Figure 10: Scatter plot of Hollis MR-5 (5-205) against Eppley PSP (27412F3) with least squares fit.

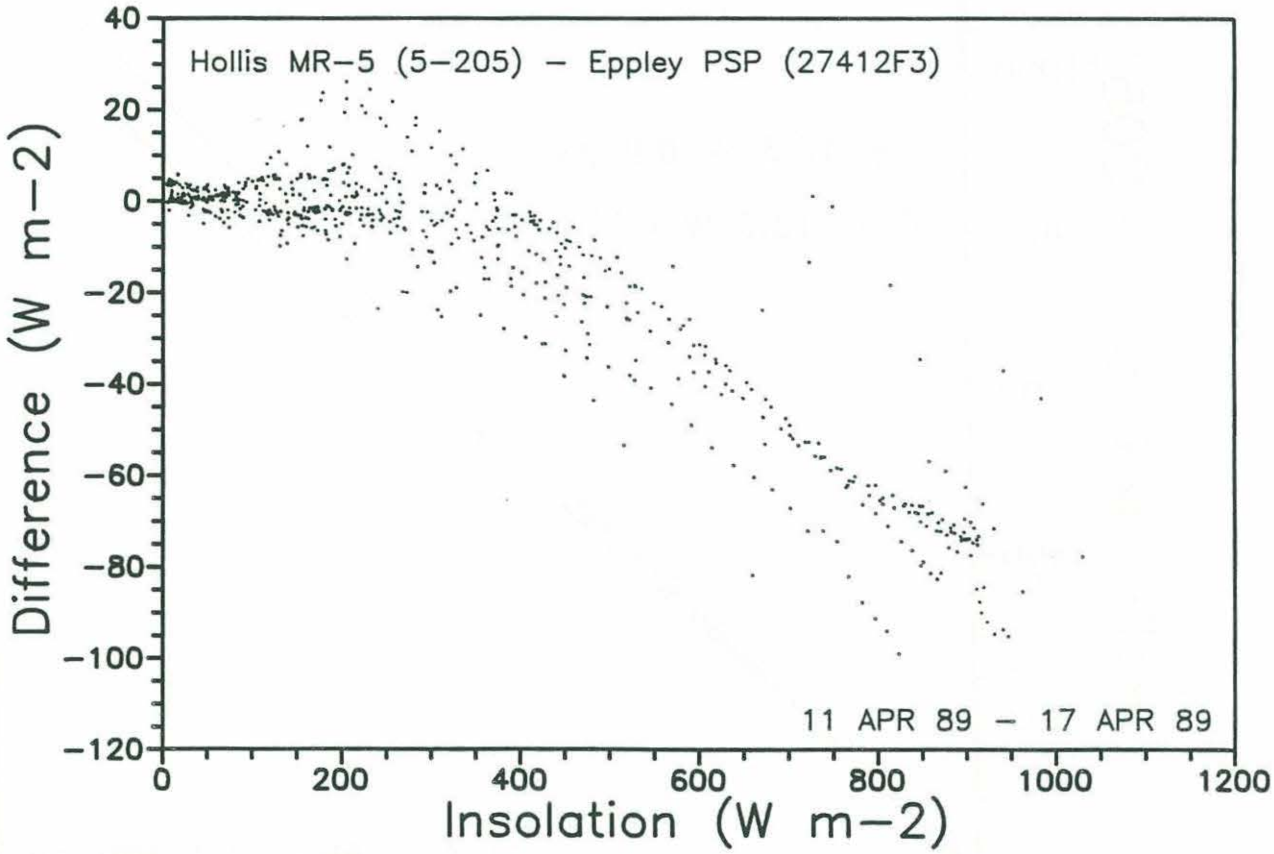

Figure 11: Scatter plot of insolation difference of Hollis MR-5 (5-205) minus Eppley PSP (27412F3) as a function of insolation.

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16. Abstract (Limit: 200 words)

Three different types of pyranometers (two of each) are tested and evaluated. The sensors include the Eppley Precision Spectral Pyranometer (PSP) which meets the World Meteorological Organization (1965) criteria for a first class pyranometer, the Eppley 8-48 Black and White Pyranometer (second class) and the Hollis MR-5 Silicon Photovoltaic Pyranometer (third class).

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